Periodic X-ray Emission from the O7 V Star θ^1 Orionis C

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ABSTRACT

We report the discovery of large-amplitude, periodic X-ray emission from the O7 V star θ^1 Orionis C, the central star of the Orion Nebula. Ten *ROSAT* HRI snapshots of the Trapezium cluster taken over the course of 21 days show that the count rate of θ^1 Ori C varies from 0.26 to 0.41 counts s^{-1} with a clear 15-day period. The soft X-ray variations have the same phase and period as Hα and He II λ4686 variations reported by Stahl et al., and are in anti-phase with the C IV and Si IV ultraviolet absorption features. We consider five mechanisms which might explain the amplitude, phase, and periodicity of the X-ray variations: (1) colliding-wind emission with an unseen binary companion, (2) coronal emission from an unseen late-type pre-main–sequence star, (3) periodic density fluctuations, (4) absorption of magnetospheric X-rays in a corotating wind, and (5) magnetosphere eclipses. The *ROSAT* data rule out the first three scenarios, but cannot rule out either of the latter two which require the presence of an extended magnetosphere, consistent with the suggestion of Stahl et al. that θ^1 Ori C is an oblique magnetic rotator. As such, θ^1 Ori C may be the best example of a high-mass analog to the chemically peculiar, magnetic Bp stars.

Subject headings: stars: individual (θ^1 Orionis C) – stars: early-type – X-rays: stars

1. Introduction

θ^1 Orionis C (HD 37022=HR 1895) is the central star of the Trapezium cluster and the principal source of ultraviolet photons illuminating the Orion Nebula (M 42). θ^1 Ori C also illuminates the population of proplyds in its vicinity (O'Dell & Wen 1994), providing some of the most direct evidence yet for circumstellar disks around low-mass pre-main–sequence (PMS) stars. It is classified as O7 V (Conti & Leep 1974) but is spectroscopically variable (Conti 1972; Walborn 1981). Conti & Alschuler (1971) and Conti (1972) also found variable inverse P Cygni emission profiles in the He II λ4686 line. Recently, Stahl et al. (1993) discovered that the long-known Hα and He II λ4686 emission variations on θ^1 Ori C exhibit a strict, stable 15.4-day periodicity, presumably the rotation period of the star. They suggested that θ^1 Ori C may be an oblique magnetic rotator akin to magnetic chemically peculiar B stars like the He-strong star σ Ori E (B2 Vpe) where the emission lines are likely to be formed in the magnetosphere above the magnetic equator (Shore & Brown 1990).

Walborn & Nichols (1994) and Stahl. et al. (1996) subsequently found C IV $\lambda\lambda 1548, 1551$ absorption variations at high velocities that are consistent with the Hα period and concluded that θ^1 Ori C possesses a corotating wind. The C IV absorption strength is minimum when the Hα and He II λ4686 emission is maximum, i.e., when the wind in our line of sight is weakest. From the phase difference between the optical emission and the UV absorption-line strength, Stahl et al. (1996) infer a rotational inclination $i \sim 45°$ and a magnetic obliquity $\beta \sim 45°$.

X-ray variability of θ^1 Ori C was first reported by Ku, Righini-Cohen, & Simon (1982) based on *Einstein* HRI observations of the Trapezium. Three deep *ROSAT* HRI exposures obtained in 1991 October, 1992 March, and 1992 September show that θ^1 Ori C varied from 0.29 to 0.45 counts s^{-1}. When folded with the ephemeris of Stahl et al. (1993), the high and low X-ray count rates corresponded to phases of maximum and minimum Hα emission,

respectively (Caillault, Gagné, & Stauffer 1994).

2. Observations and Results

During the period 1995 September 1–21, the *ROSAT* HRI (cf. David et al. 1996) obtained 10 observations of the Trapezium each separated by approximately two days and each consisting of two satellite orbits. A light curve for θ^1 Ori C was generated by summing counts within a $10''$ (90% power) radius circle centered on the emission peak, subtracting a local background, and dividing the net counts by the dead-time corrected exposure time for each orbit. The source region dimensions were chosen to exclude essentially all counts from other Trapezium sources. In Figure 1, we plot the HRI light curve of θ^1 Ori C. Images of individual orbits revealed that for 7 of the 20 orbits, the standard processing software was unable to generate an adequate aspect solution. Consequently, point sources in these 7 images appear to be smeared along the SE–NW axis. For these orbits, source counts were extracted from an ellipse with major and minor axes of $13.1''$ and $9.2''$, respectively, and position angles ranging from $40°$–$50°$. These points are indicated in Fig. 1 with crosses.

EDITOR: PLACE FIGURE 1 HERE.

In Fig. 1, the upper axis indicates the corresponding phase using the ephemeris of Stahl et al. (1996), where $P = 15.422$ d, $MJD = 48832.5$, and phase 0.0 correspond to maximum Hα emission. Also plotted are the 1991 Oct 2, 1992 Mar 22, and 1992 Sep 14 count rates and phases (open circles). Fitting a simple sine curve to the X-ray count rates with a period of 15.422 d yields a low-state count rate of 0.26 counts s^{-1} and an amplitude of 0.15 counts s^{-1}. The fit is plotted in Fig. 1. Leaving the period as a free parameter, we find a period of 16.0 ± 3.8 days (1σ error). The soft X-ray emission appears to vary in phase with the Hα emission and with a very similar period.

Based on the optical extinction estimates of Breger, Gehrz, & Hackwell (1981), the interstellar column density in the θ^1 Ori C line of sight is likely to be $(3 \pm 1) \times 10^{21}$ cm^{-2}. Assuming a distance of 440 pc, the 0.1–2.0 keV X-ray luminosity of θ^1 Ori C at phase ~ 0.5 is $L_{\rm X} \sim 4.6 \times 10^{32}$ ergs s^{-1} (corrected for interstellar absorption). If we assume no major changes in the spectral shape at X-ray maximum, the 0.15 counts s^{-1} HRI variability amplitude corresponds to $\Delta L_{\rm X} \sim 2.6 \times 10^{32}$ ergs s^{-1}.

3. Discussion

We discuss the X-ray variability in the context of five different models: (1) colliding-wind emission with an unseen lower-mass companion, (2) coronal emission from an unseen lower-mass companion, (3) periodic density variations, (4) absorption of magnetospheric X-rays in a corotating wind, and (5) magnetosphere eclipses.

3.1. Colliding Winds

For the first two scenarios, we assume that θ^1 Ori C has an unseen PMS companion. While there is no compelling evidence that θ^1 Ori C is a binary, many high-mass stars in the Trapezium are spectroscopic binaries (Abt, Wang, & Cardona 1991). Stahl et al. (1996) did find that a number of θ^1 Ori C's photospheric lines show irregular ~ 2 km s^{-1} radial-velocity variations, suggesting an upper limit to the companion's mass $M \sin i \sim 0.27 M_\odot$, assuming an O star mass $M \sim 36 M_\odot$ (Howarth & Prinja 1989). If 15.4 d is the orbital period, then a lower limit for the binary separation is $a \sim 85 R_\odot$. In colliding-wind models, the X-rays arise in a shock region where the wind of a hot, massive star collides with either the wind or the outer atmosphere of the companion. We calculate the expected X-ray emission from θ^1 Ori C via this mechanism by comparing it to the well-studied example of γ Velorum,

a Wolf-Rayet binary (O9 I + WC8) in which the WR secondary possesses a very massive wind with $\dot{M} \sim 8.8 \times 10^{-5} M_\odot$ yr^{-1} and $v_\infty \sim 1520$ km s^{-1}. Willis, Schild, & Stevens (1995) predict $L_{\rm X} \sim 10^{32}$ ergs s^{-1} resulting from the γ Vel colliding-wind shock region.

In the case of θ^1 Ori C, the wind is variable and published values of the terminal wind speed are discordant. Prinja, Barlow, & Howarth (1990) used the narrow absorption component in the C IV profile and estimated $v_\infty \sim 510$ km s^{-1}. Walborn & Nichols (1994) identified a broad, variable, high-velocity component in the C IV profile and determined $v_\infty \sim 3600$ km s^{-1}. In order to maximize the effect of colliding winds, we assume $\dot{M} \sim 4 \times 10^{-7} M_\odot$ yr^{-1} and $v_\infty \sim 510$ km s^{-1} for θ^1 Ori C; in the most optimistic case, the T Tauri companion might have $\dot{M} \sim 4 \times 10^{-7} M_\odot$ yr^{-1} (Levreault 1988) and $v_\infty \sim 200$ km s^{-1} (Natta, Giovanardi, & Palla 1988). Using these wind parameters in eq. (10) of Stevens, Blondin, & Pollock (1992), we find that the maximum expected X-ray luminosity of θ^1 Ori C from colliding winds would be comparable to that observed on γ Vel.

Although the wind parameters have been chosen to maximize colliding-wind emission, the predicted $L_{\rm X}$ falls short of the observed X-ray variability amplitude by a factor of three. Moreover, the collision of such slow winds may not produce sufficient shocks to heat the interaction region to $T > 1$ MK. If instead we use $v_\infty \sim 3600$ km s^{-1} for the terminal wind speed of θ^1 Ori C, the predicted X-ray luminosity is a factor of at least 25 lower because of the lower wind density in the interaction region. In this case, the sharp peak at phase 0.0 predicted by the model of Willis et al. (1995) is inconsistent with the smoothly varying sinusoidal X-ray emission observed on θ^1 Ori C. Also, colliding winds cannot account for the smooth variation with phase of the equivalent width of the C IV absorption line observed by Walborn & Nichols (1994) and Stahl et al. (1996). It should be noted that the Stevens et al. (1992) model assumes spherically symmetric mass loss while mass loss from T Tauri stars is often collimated in bipolar jets (e.g., Shu et al. 1994). It is also unclear how long

a massive accretion disk (which drives mass loss in T Tauri stars) might survive in close proximity to an O7 V star. While there are many complicating factors one could include in the colliding-wind scenario, we think it unlikely that these complications would significantly improve the agreement between the model and the observations.

3.2. A Low-Mass Coronal Companion

Next, we consider coronal X-ray emission from an unseen, PMS companion whose coronal X-ray emission is being eclipsed by the O-star or severely attenuated by the O-star wind at the 15.422 d orbital period. Since the amplitude of the HRI variations corresponds to $\Delta L_{\rm X} \sim 2.6 \times 10^{32}$ ergs s^{-1}, this must be a lower limit to the companion's X-ray luminosity. Since the most X-ray luminous low-mass star in the entire Orion region, P1817, has $L_{\rm X} \sim 5 \times 10^{31}$ ergs s^{-1} (Gagné, Caillault, & Stauffer 1995), it is unlikely that a low-mass star can account for the observed variations. Moreover, as has been pointed out by Stahl et al. (1996), a low-mass companion cannot account for the luminosity of the Hα and He II λ4686 variations. Given the the small-amplitude radial-velocity variations, a more massive companion (e.g., an O or early-B star) could exist if the binary orbit were in the plane of the sky ($i \approx 0$); but, in this case, we do not expect significant X-ray variability.

3.3. Periodic Density Fluctuations

To our knowledge, ζ Puppis (O4 I(n)f) is the only other candidate O-type magnetic rotator. Moffat & Michaud (1981) report periodic Hα variations and propose a rotational period of 5.075 d for ζ Pup. Berghöfer et al. (1996) report 6% variations in the 0.9–2.0 keV *ROSAT* PSPC flux and a 2σ peak in the X-ray power spectrum near 16.7 hr. Contemporaneous Hα spectra show profile variations consistent with the Moffat & Michaud

(1981) period of 5.075 d. The residual profile variations also indicate a weak peak in the Hα emission power spectrum near the X-ray period of 16.7 hr. Berghöfer et al. interpret the X-ray–Hα correlation as evidence for periodic density fluctuations at the base of the wind. Interestingly, the PSPC time series does not indicate any variability at the 5.1-d rotation period. Nonetheless, the periodic Hα and ultraviolet variations and the possible presence of correlated X-ray–Hα emission in ζ Pup and θ^1 Ori C is noteworthy. Berghöfer et al. (1996) interpret the 16.7 hr period as pulsations or cyclically repeating azimuthal structures. They suggest that either of these will produce periodic density variations at the photosphere which propagate through the wind, producing enhanced Hα, and X-ray emission seen from different characteristic heights in the wind. Berghöfer et al. (1996) propose that the emissions have the same apparent phase because the phase shift between the X-ray and Hα emission regions is, fortuitously, ~ 1. In the case of θ^1 Ori C, the sound crossing time through the wind is short ($t \lesssim 1$ d out to $r \sim 10R_\star$) compared to the 15.4-d period of θ^1 Ori C. Consequently, a density wave resulting from non-radial pulsations might lead to apparently coherent variations. However, the lowest non-radial pulsation modes for main-sequence O stars have periods in the range 0.5–2.0 d (Baade 1986), much shorter than the observed 15.4 d period.

3.4. Absorption in a Corotating Wind

For the next two scenarios, we assume that the 15.422 d periodicity is the rotational period of a single O star. The periodic C IV and Si IV profile variations seen by Walborn & Nichols (1994) and Stahl et al. (1996) appear to require a non-spherically symmetric, corotating wind. The tremendous torque required to maintain a corotating wind also suggests an extended magnetic field geometry. As has been pointed out by Stahl et al. and Walborn & Nichols, the C IV, Hα, and He II variations on θ^1 Ori C are reminiscent of the

oblique magnetic rotator σ Ori E (B2 Vpe). On σ Ori E, mass loss occurs preferentially along open magnetic field lines over the magnetic poles, while, at lower magnetic latitudes, field lines close inside the Alfvén radius, funneling wind material towards the magnetic equator. Bolton (1994) suggests that the region of closed magnetic field lines (the magnetosphere) extends out to $R \sim 5R_{\star}$. If phases of maximum mass loss on θ^1 Ori C correspond to phases of maximum C IV absorption, then we expect one magnetic pole to pass our line of sight around phase 0.5. (Stahl et al. 1996).

We suggest that most of θ^1 Ori C's X-ray emission is produced in the magnetosphere of an oblique magnetic rotator. Although O-star X-rays are generally interpreted as emission from shock regions distributed throughout the wind (e.g., Owocki, Castor, & Rybicki 1988), X-ray emission from θ^1 Ori C is not typical of most single, main-sequence O stars. First, θ^1 Ori C is the only known O star with large-amplitude, periodic X-ray variability. Second, θ^1 Ori C's peak X-ray activity level, $L_{\rm X}/L_{\rm bol} \sim 1.8 \times 10^{-6}$, is higher (by a factor of five) than any other single O star detected in the *ROSAT* all-sky survey (Berghöfer, Schmitt, & Cassinelli 1996). Third, the *ASCA* SIS spectrum of the Trapezium (Yamauchi et al. 1996) indicates very high temperature plasma with $T > 20$ MK. Although the SIS cannot spatially resolve θ^1 Ori C from surrounding lower-mass stars, the HRI images and the PSPC low-resolution spectra suggest that some of the high-temperature emission must be associated with θ^1 Ori C. Conventional O-star shock models do not predict sufficiently fast shocks to produce such hot plasma. On the other hand, magnetically confined plasma (e.g, in coronal loops on the Sun and other late-type stars) can be heated to very high temperatures.

Assuming that X-rays from the magnetosphere are being absorbed in the wind, X-ray variability would arise from varying wind absorption. The amount of excess absorbing material can be inferred from the C IV excess equivalent width at high velocities around

phase 0.5, $W_{1548,1551} \sim 2.2$ Å (Walborn & Nichols 1994). Assuming that the absorbing material is optically thin in C IV, we find a lower limit to the excess column density $N_{\rm CIV} \sim 3.7 \times 10^{14}$ cm^{-2}. Howarth & Prinja (1989) determine $N_{\rm CIV} \sim 9.4 \times 10^{14}$ cm^{-2} from the P Cygni profile at low velocities. If the wind and the absorbing region have approximately the same abundance and ionization, then 25–30% of the column density measured at phase 0.5 comes from the overlying absorption region. Since the high-velocity C IV absorption is not observed at phase 0.0, can this column density difference account for the observed X-ray variability amplitude?

In order to estimate the X-ray spectral shape of θ^1 Ori C, we have analyzed the *ROSAT* PSPC spectrum of the Trapezium obtained in 1991 March over 4 d spanning phases 0.36–0.63, i.e., near θ^1 Ori C X-ray minimum. We have simulated *ROSAT* HRI count rates at phases 0.0 and 0.5 in XSPEC (Arnaud 1996) by fitting the PSPC spectrum obtained near phase 0.5 and varying the column density in the overlying absorption region. The fit parameters are not well constrained, but the simulations suggest that a $\sim 25\%$ decrease in the wind column density would result in a $\sim 40\%$ increase in the HRI count rate from phase 0.5 to 0.0. More detailed modeling of spatially resolved X-ray spectra is required, but our preliminary estimates suggest that absorption in the overlying, corotating wind of an oblique magnetic rotator may be a viable mechanism for the observed X-ray variability.

3.5. Magnetosphere Eclipses

On an O-type magnetic rotator, X-ray variability might result from eclipses of the magnetosphere and/or from varying absorption in the overlying, corotating wind. If the magnetosphere on θ^1 Ori C extends out to many stellar radii like it does on σ Ori E and if $i \sim 45°$, then the X-ray variations are not likely to arise from eclipses. However, if the magnetosphere were closer to the stellar surface (i.e., 1–2 $R_\star$), then eclipses could

produce smooth X-ray variations. This scenario can be tested with X-ray spectra obtained at opposite phases. If the X-ray spectra do not indicate any appreciable change in the absorbing column density from X-ray minimum to X-ray maximum, then the variability is most likely due to eclipses.

4. Challenges for the Oblique Magnetic Rotator Model

The first two scenarios, which require the presence of an unseen binary companion, probably cannot account for the smooth, large-amplitude X-ray variations seen on θ^1 Ori C. Furthermore, there is little evidence that θ^1 Ori C is a binary: the photospheric lines only show small, irregular radial-velocity variations (Stahl et al. 1996). Such variability is characteristic of atmospheres of luminous O stars and is not strong evidence for a companion (Bieging, Abbott, & Churchwell 1989). The period of the X-ray and Hα emission is not compatible with non-radial pulsations causing density fluctuations in the O star wind.

The phase, period, and variability amplitude of the X-ray emission on θ^1 Ori C do appear to be consistent with either of the last two scenarios. Like Stahl et al. (1996), we, too, conclude that the 15-d period is the rotation period of the O star and that most of the observed variable emission and absorption phenomena can be explained if θ^1 Ori C is an oblique magnetic rotator. Nonetheless, a few outstanding questions remain.

First, and most importantly, it would be useful to measure the longitudinal magnetic field strength as a function of phase. Establishing the existence and location of one or more magnetic poles on θ^1 Ori C would represent the first definitive detection of magnetic fields on any O star. A surface magnetic field of a few hundred Gauss may be sufficient to produce wind corotation out to 10 stellar radii. However, such a small field may be difficult to detect because it would produce Zeeman shifts of only a few mÅ compared to a polarized

line width of ~ 1 Å (Otmar Stahl, private communication). Alternatively, the Hanle effect can be used to detect polarization differences in the C IV $\lambda\lambda 1548, 1551$ resonance lines for massive stars whose longitudinal B-field is less than 1 kG. The Hanle effect refers to a change in the polarization of resonantly scattered photons as a result of Larmor precession of the scattering electron in a magnetic field (see Cassinelli & Ignace 1996).

Second, $v \sin i \sim 50$ km s^{-1}, as measured from photospheric O III $\lambda\lambda 3756, 3760$ line profiles, is too high. If the 15.4 d period is the rotation period of the star, then $v \sin i$ must be less than $v_{\rm eq} \sim 30$ km s^{-1}, assuming $R_\star \sim 8 R_\odot$ (Howarth & Prinja 1989). Non-rotational broadening mechanisms, which have not been taken into account in the $v \sin i$ determination of Stahl et al. (1996), may explain some of the discrepancy. Possible broadening mechanisms include: stronger stark broadening due to higher gravity or atypically large macroturbulence, related to the peculiar optical line-profile variations. We note, however, that most main-sequence O stars show little evidence of macroturbulence (Ebbets 1979) and classical Doppler broadening measurements are generally adequate for determining $v \sin i$ in slowly rotating early-type stars like θ^1 Ori C (Collins & Truax 1995).

Finally, modeling of magnetospheric X-ray emission with non-spherically symmetric wind geometries is essential. Upcoming observations of the Trapezium with *ASCA* at opposite phases of θ^1 Ori C may help distinguish between the two competing hypotheses for the X-ray variability observed by *ROSAT*. Because of source confusion in the Trapezium, though, a conclusive test may only be possible with the *AXAF* CCD Imaging Spectrometer.

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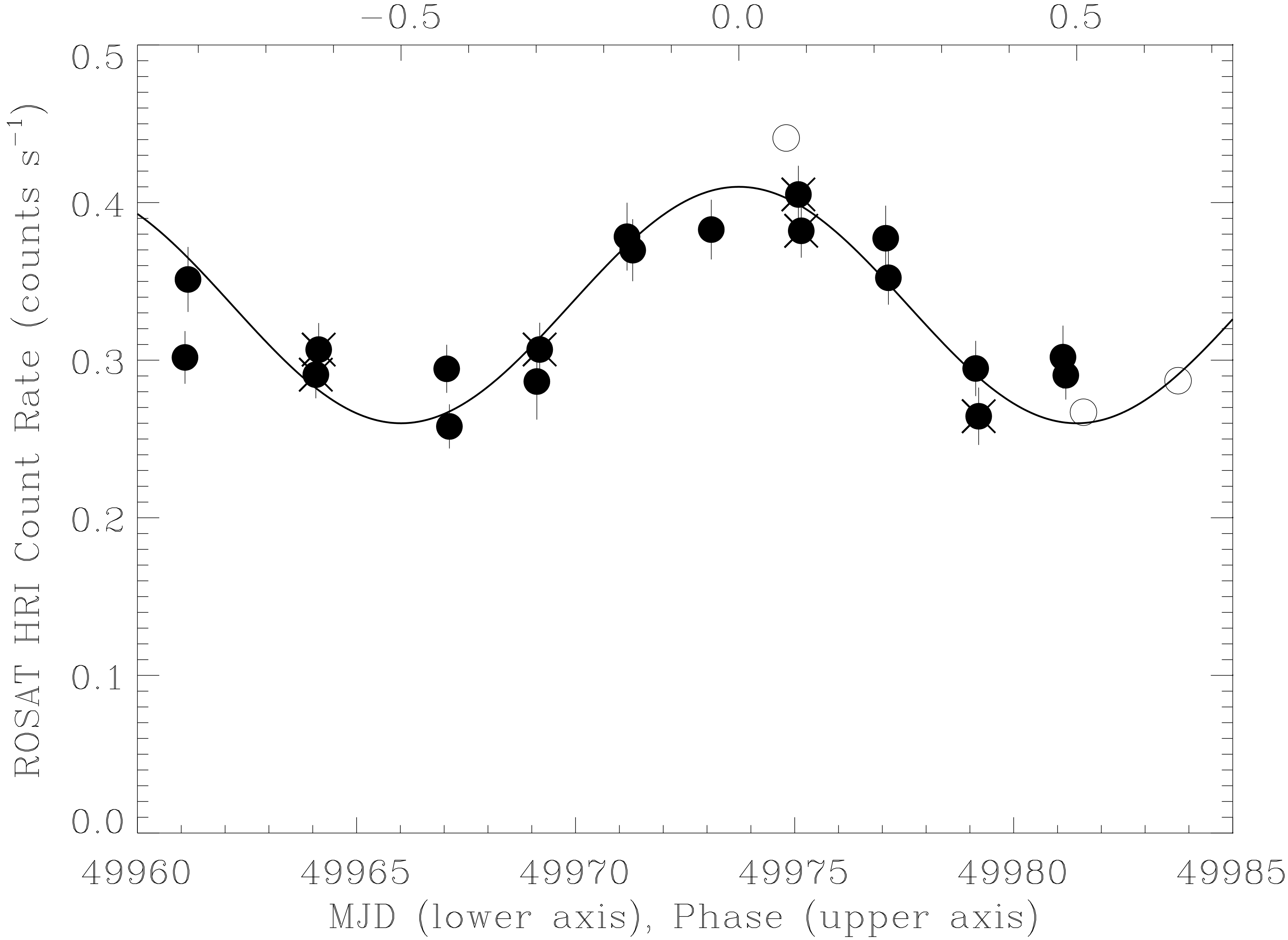
Fig. 1.— *ROSAT* HRI lightcurve of θ^1 Ori C. HRI count rates and 1σ uncertainties are plotted versus MJD for observations obtained 1995 Sep 1–21 (filled circles); crosses indicate orbits with uncertain count rates (see §2). The upper axis indicates the corresponding phase of θ^1 Ori C based on the ephemeris of Stahl et al. (1996). The count rates and phases from 1991 Oct 2, 1992 Mar 22, and 1992 Sep 14 are plotted as open circles.


ROSAT HRI Count Rate (counts s^{-1})
MJD (lower axis), Phase (upper axis)
−0.5
0.0
0.5
0.0
0.1
0.2
0.3
0.4
0.5
49960
49965
49970
49975
49980
49985